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Modeling the Chelyabinsk Impact in 3D

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On February 15th, 2013, a large meteor entered the atmosphere over the city of Chelyabinsk, Russia. Although it did not strike the Earth's surface, the blow-up of the object was impressive. There were numerous witnesses (cf. youtube videos provided in many cases by dashboard-mounted cameras in vehicles), and the fireball was seen over several Russian cities. A good deal of damage was done by the shock wave from the exploding bolide. There were broken windows in buildings and numerous injuries, though fortunately no fatalities. The impact was likely the largest known event since the Tunguska impact over a century ago.

Subsequent analysis of the event, including orbit analysis and recovery of meteorite fragments, suggest that the impactor was ~ 17-20 m in diameter, striking the atmosphere at 19.0 km s^{-1} at an angle of 75º from the vertical [1]. The object composition was chondritic of the LL5 type [2] with a bulk density of ~ 3.3 gm cm^{-3}. Further discussion and analysis of the impact observations can be found in the discussion by [3].

The event underscores the potential hazard posed by the impact of asteroids on the Earth. Even non-fatal impacts of small objects can cause significant amounts of damage. As such, these events need to be understood and the hazards they pose need to be characterized for mitigation purposes.

Beyond the hazard aspect, terrestrial meteor impacts are a fascinating example of complex physical processes in the natural world. They present strong challenges for modeling of the type described in this abstract. At the same time, the wealth of data generated by these events, and this one in particular, afford a unique set of tests: literal "ground truth" applications of modeling techniques. Given the parameters of the event (object size, velocity, impact angle, composition, and material properties), it should be possible to match the observations, in particular the energy deposition along the bolide's track.

3D Hydrodynamic Simulations of the Chelyabinsk impact

Simulation of the Chelyabinsk impact is challenging. Modeling an object of this size demands high resolution (grid cells Δx of order a meter or smaller); combined with the velocity v_i of the impact, the Courant condition for the simulation requires timesteps $\Delta t < \Delta x/v_i \sim 10^{-5}$ s. The challenge is increased by the high inclination of the bolide's path, which increases the timescale of the event by a factor ~4 from a vertical impact starting at z=100 km height, to ~ 10 s, thus requiring approximately 10^6 timesteps for a single calculation.

We report results from attempts at modeling the impact using the CTH hydrocode at low-to-moderate resolution (grid cells Δx =1.25 m in size). Developed at Sandia National Laboratory, CTH[4] is a highly advanced code widely used in the planetary science community. It makes use of material strength models and advanced tabular equations of state such as ANEOS and the SESAME library from Los Alamos National Laboratory.

The impactor is modeled as a 10-meter radius basalt sphere moving at v_i=19.03 km s^{-1}, into an atmospheric profile (vertical scale height H=7.2 km) at an impact angle of 74.6º from the vertical. We use the SESAME equation of state with a basic material strength model (GEO) that is included in CTH. The impactor's initial height at t=0 is z=80 km. In these calculations we find the impactor loses mass and energy primarily by ablation as opposed to fragmentation to large pieces, hydrodynamic instability or spreading by aerodynamic pressure gradients ("pancaking"). Fig. 1 shows density on a logarithmic scale along one of the mid-planes of the computation. The impactor is made of basalt as modeled using the SESAME EOS. The maximum resolution is Δ=1.25 m or 8 resolution elements for the impactor radius of 10 m ("R8").

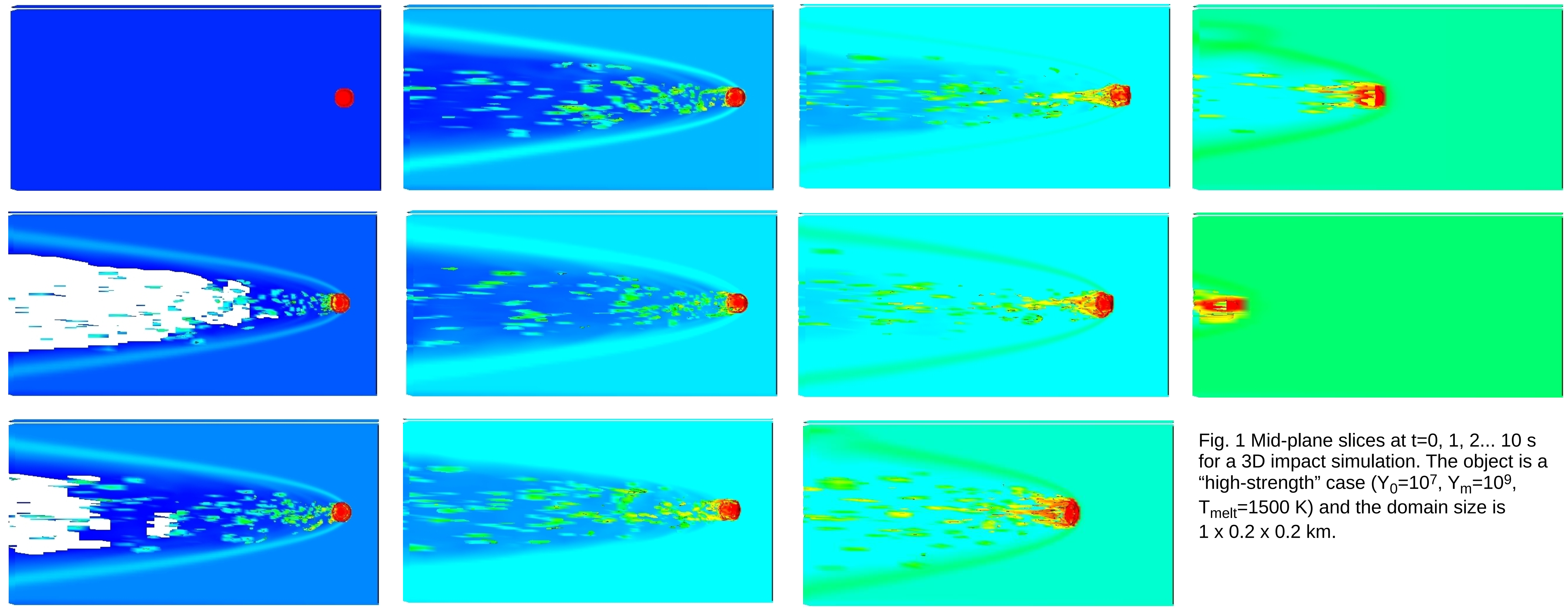

Fig. 1 Mid-plane slices at t=0, 1, 2... 10 s for a 3D impact simulation. The object is a "high-strength" case ($Y_0=10^7$, $Y_m=10^9$, T_{melt}=1500 K) and the domain size is 1 x 0.2 x 0.2 km.

Initial Results – 3D calculations

Figs. 2-6 show the mass m in the computational domain (the "box"), along with the kinetic energy deposition deposition dE/dz, where $E=mv^2/2$ is the kinetic energy. The quantities are plotted as function of (true) height z above the ground. In these calculations, we are interested in testing the effects of the box size and material strength on the results. We have carried out three calculations for each case, in which initial conditions (such as impactor initial position) are changed by trivial amounts, to assess whether the energy deposition curves display sensitivity to initial conditions ("chaos").

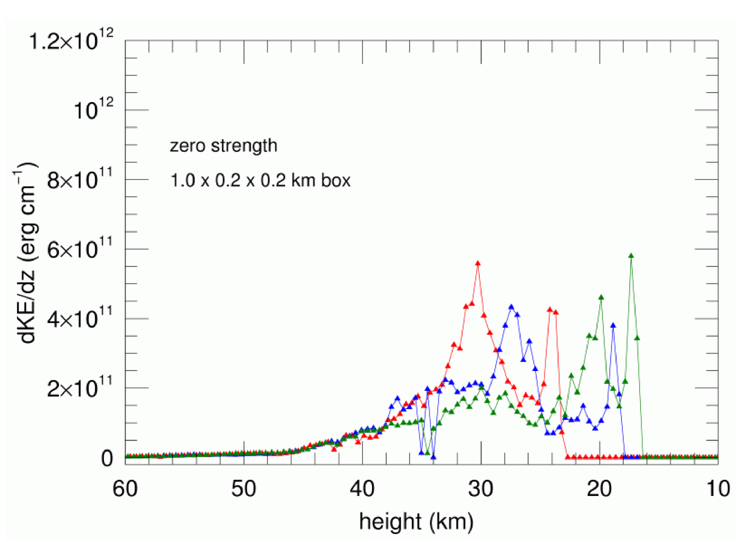

Fig. 2. Plot of kinetic energy deposition (dE/dz) as a function of height for strengthless impactors in a box of dimension 1x0.2x0.2 km.

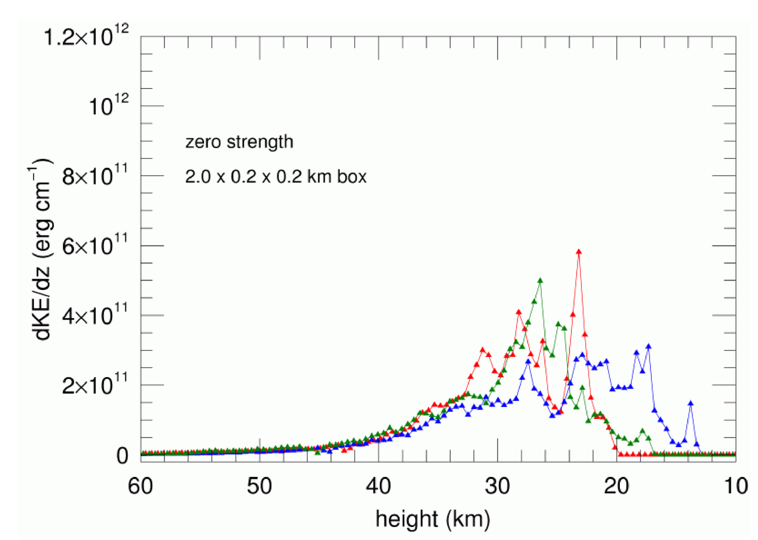

Fig. 3. Plot of kinetic energy deposition (dE/dz) as a function of height for strengthless impactors in a box of dimension 2x0.2x0.2 km.

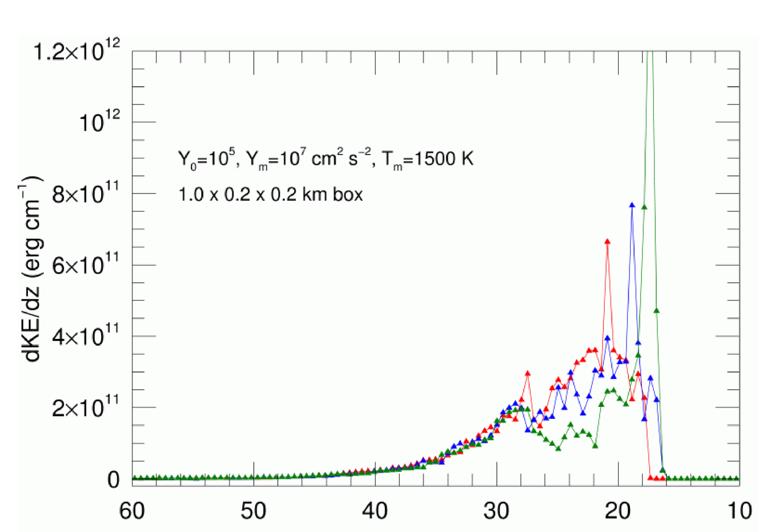

Fig. 4. Plot of kinetic energy deposition (dE/dz) as a function of height for low-strength impactors in a box of dimension 1x0.2x0.2 km.

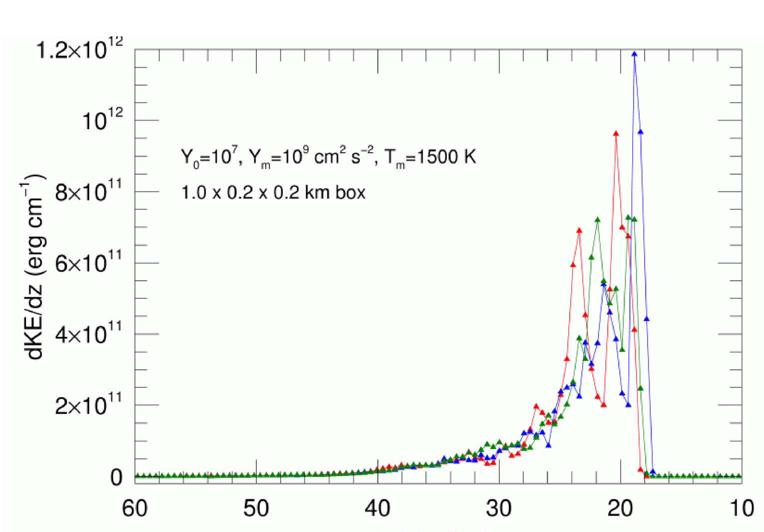

Fig. 5. Plot of kinetic energy deposition (dE/dz) as a function of height for high-strength impactors in a box of dimension 1x0.2x0.2 km.

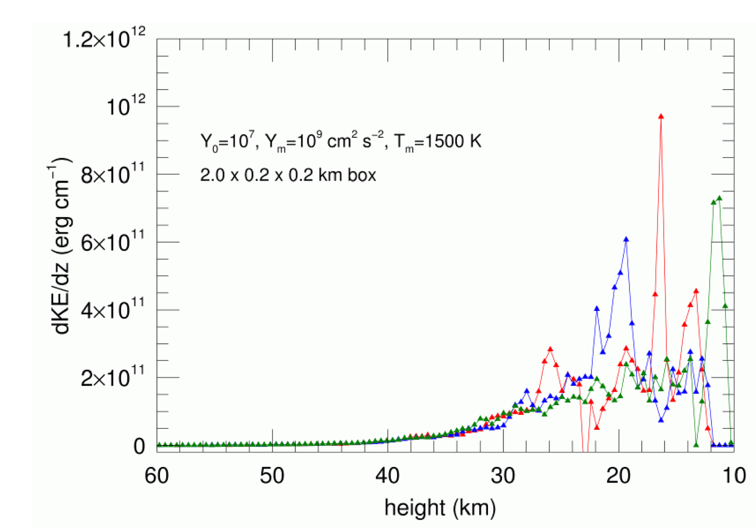

Fig. 6. Plot of kinetic energy deposition (dE/dz) as a function of height for high-strength impactors in a box of dimension 2x0.2x0.2 km.

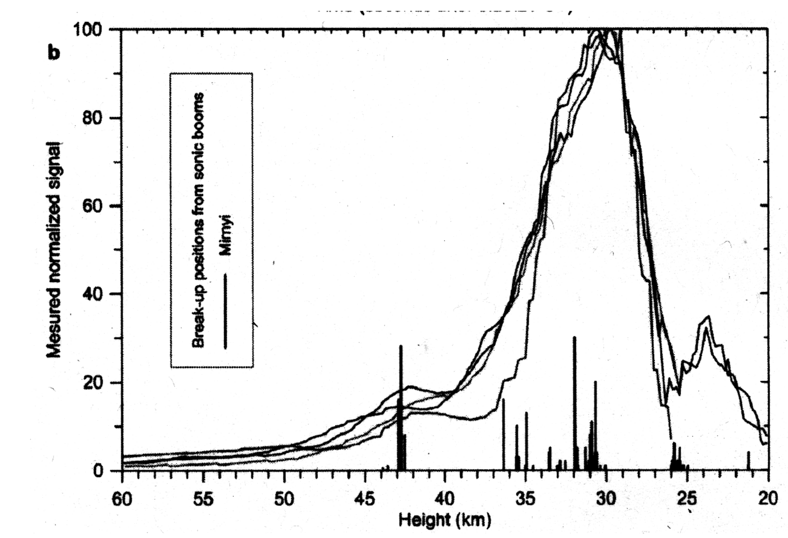

Fig 7. Light curve of the Chelyabinsk impact as observed [3].

Discussion

Overall the energy deposition curves shown in Figs. 2-6 agree qualitatively with the observed light curve reconstructed from observations [3] (Fig 7). Peak energy deposition of the calculations matches best with zero-or low-strength impactors; if anything the height by which 50% of the energy is deposited is a few km too low, even for zero-strength objects. Closer inspection of the results (cf. Fig. 1), however, suggests that the simulation behavior does not match the observed behavior: kinetic energy in the simulations is lost by ablation of the main object as a single body, whereas the sonic booms observed suggest energy loss proceeded by the break-up of the object into more-or-less discrete smaller bodies. Modeling the impactor as a loosely bound collection of smaller and stronger sub-units may be able to reproduce this behavior.

An important aspect of the calculations can be seen in all four sets of impact calculations that have been carried out (Figs 2-6), namely sensitivity to initial conditions, or "dynamical chaos". Tiny changes in initial conditions such as the displacement of impactors on the grid by half a grid cell (62.5 cm) lead to order-unity differences in the energy deposition curves. Similar behavior has been found in simulations of the SL9 impacts into Jupiter's atmosphere [5], using a completely different code (ZEUSMP), suggesting the numerical behavior may reflect a real phenomenon.

References

[1] Yeomans and Chodas 2013. http://neo.jpl.nasa.gov/news/fireball_130301.html [2] Kohout *et al*. 2014 *Icarus* **228**, 78. [3] Borovicka *et al*. 2013, *Nature* **503**, 235. [4] McGlaun, J. M., *et al*., 1990. *Int. J. Impact Engr.* **10**, 351-360. [5] Korycansky *et al.*. 2005, Astrophys J. **646**, 642.

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